UWThPh-1994-48
AUE-08-94, US-94-06
October 1994

Electric Dipole Moments of Neutron and Electron in Two-Higgs-Doublet Model with Maximal CP violation

Takemi HAYASHI[(a)], **Yoshio KOIDE**[(b) 1]

Masahisa MATSUDA[(c) 2], **Morimitsu TANIMOTO**[(d)], **Seiichi WAKAIZUMI**[(e)]

[(a)] *Kogakkan University, Ise, Mie 516, JAPAN*

[(b)] *Department of Physics, University of Shizuoka, 52-1 Yada, Shizuoka 422, JAPAN*

[(c)] *Department of Physics and Astronomy, Aichi University of Education Kariya, Aichi 448, JAPAN*

[(d)] *Institut für Theoretische Physik, Universität Wien Boltzmanngasse 5, A-1090 Wien, AUSTRIA* [3]

[(e)] *Department of Physics, School of Medical Sciences, University of Tokushima Tokushima 770, JAPAN*

ABSTRACT

We study the electric dipole moments(EDM) of the neutron and the electron in the two-Higgs-doublet model, in the case that CP symmetry is violated maximally in the neutral Higgs sector. We take account of the Weinberg's operator $O_{3g} = GG\tilde{G}$ as well as the operator $O_{qg} = \overline{q}\sigma\tilde{G}q$ for the neutron, and the Barr-Zee diagrams for the electron. It is found that the predicted neutron EDM could be considerably reduced by the destructive contribution of the two Higgs scalars to get the lower value than the experimental bound. As to the electron EDM, the predicted value is smaller in one order than the experimental one.

[1]E-mail:koide@u-shizuoka-ken.ac.jp
[2]E-mail:masa@auephyas.aichi-edu.ac.jp
[3]Permanent address:Science Education Laboratory, Ehime University,790 Matsuyama, JAPAN

The physics of CP violation has attracted much recent attention in the light that the B-factory will go on line in the near future. The central subject of the B-factory is the test of the standard model(SM), in which the origin of CP violation is reduced to the phase in the Kobayashi-Maskawa matrix[1]. However, there has been a general interest in considering other approaches to CP violation since many alternate sources exist. The electric dipole moment(EDM) of the neutron is of central importance to probe these new sources of CP violation, because it is very small in SM while it can be larger in the other models. By begining with the papers of Weinberg[2], there has been considerable renewed interest in the EDM induced by CP violating neutral Higgs sector. Some studies[3,4,5] revealed numerically the importance of the "chromo-electric" dipole moment, which arises from the three-gluon operator $GG\tilde{G}$ found by Weinberg[2] and the light quark operator $\overline{q}\sigma\tilde{G}q$ introduced by Gunion and Wyler[3], in the neutral Higgs sector. We know the simplest extension of SM Higgs sector, namely the type II two-Higgs-doublet model(THDM)[6], which demonstrates explicit or spontaneous CP violation[7] in its neutral sector if the soft breaking term of the discrete symmetry is included. Many authors have already studied this model and proposed to search for CP violating observables directly or indirectly in the Higgs sectors[8,9,10].

The estimates of the maximal values of those observables are important to search for CP violating effect in the Higgs sector. We have already studied the Higgs potential to give maximal CP violation and its effect on the ρ parameter[11,12]. We have found that the maximal CP violation is realized under the fixed values of $\tan\beta$ with two constraints of parameters in the Higgs potential[12]. The purpose of this paper is to calculate the values of EDM of the neutron and the electron in THDM with maximal CP violation, taking account of the contribution of the "chromo-electric" dipole moment. This result will give us constraints of CP violating Higgs sector by comparing with the

experimental bounds.

First, we discuss the maximal CP violation in the THDM, where the Higgs potential with CP violating terms is written as[13]:

$$
\begin{aligned}
V_{\text{Higgs}} &= \frac{1}{2}g_1(\Phi_1^\dagger\Phi_1 - |v_1|^2)^2 + \frac{1}{2}g_2(\Phi_2^\dagger\Phi_2 - |v_2|^2)^2 \\
&+ g(\Phi_1^\dagger\Phi_1 - |v_1|^2)(\Phi_2^\dagger\Phi_2 - |v_2|^2) \\
&+ g'|\Phi_1^\dagger\Phi_2 - v_1^* v_2|^2 + \mathrm{Re}[h(\Phi_1^\dagger\Phi_2 - v_1^* v_2)^2] \\
&+ \xi\left[\frac{\Phi_1}{v_1} - \frac{\Phi_2}{v_2}\right]^\dagger \left[\frac{\Phi_1}{v_1} - \frac{\Phi_2}{v_2}\right] ,
\end{aligned}
\tag{1}
$$

where Φ_1 and Φ_2 couple with the down-quark and the up-quark sectors respectively and the vacuum expectation values are defined as $v_1 \equiv <\Phi_1^0>_{vac}$ and $v_2 \equiv <\Phi_2^0>_{vac}$. We do not concern ourselves here with a specific model of CP violation, but instead consider a general parametrization using the notation developed by Weinberg[13]. We take the coupling constant h in eq.(1) to be real and set

$$
v_1^* v_2 = |v_1 v_2| \exp(i\phi) , \tag{2}
$$

as a phase convension. We define the neutral components of the two Higgs doublets using three real fields ϕ_1, ϕ_2, ϕ_3 and the Goldstone boson χ^0 as follows:

$$
\begin{aligned}
\Phi_1^0 &= \frac{1}{\sqrt{2}}\{\phi_1 + \sqrt{2}v_1 + i(\cos\beta\chi^0 - \sin\beta\phi_3)\} , \\
\Phi_2^0 &= \frac{1}{\sqrt{2}}\{\phi_2 + \sqrt{2}v_2 + i(\sin\beta\chi^0 + \cos\beta\phi_3)\} ,
\end{aligned}
\tag{3}
$$

where $\tan\beta \equiv v_2/v_1$. The real fields ϕ_1 and ϕ_2 are scalar particles while ϕ_3 is pseudo-scalar in the limit of CP conservation. CP violation occurs via the scalar-pseudoscalar interference terms in the neutral Higgs mass matrix. In this basis, the mass matrix elements are given as

$$
M_{11}^2 = 2g_1|v_1|^2 + g'|v_2|^2 + \frac{\xi + \mathrm{Re}(hv_1^{*2}v_2^2)}{|v_1|^2} ,
$$

$$
\begin{aligned}
M_{22}^2 &= 2g_2|v_2|^2 + g'|v_1|^2 + \frac{\xi + \mathrm{Re}(hv_1^{*2}v_2^2)}{|v_2|^2} \ , \\
M_{33}^2 &= (|v_1|^2 + |v_2|^2)\left[g' + \frac{\xi - \mathrm{Re}(hv_1^{*2}v_2^2)}{|v_1v_2|^2}\right] \ , \\
M_{12}^2 &= |v_1v_2|(2g + g') + \frac{\mathrm{Re}(hv_1^{*2}v_2^2) - \xi}{|v_1v_2|} \ , \\
M_{13}^2 &= -\frac{\sqrt{|v_1|^2 + |v_2|^2}}{|v_1^2v_2|}\mathrm{Im}(hv_1^{*2}v_2^2) \ , \\
M_{23}^2 &= -\frac{\sqrt{|v_1|^2 + |v_2|^2}}{|v_1v_2^2|}\mathrm{Im}(hv_1^{*2}v_2^2) \ ,
\end{aligned}
\tag{4}
$$

where the mass matrix is the symmetric one. Maximal CP violation is defined on a new basis by Georgi[14], where the Goldstone boson decouples from the Φ_2 doublet, since the gauge couplings of the Higgs bosons are diagonal in this basis. The neutral Higgs scalars $\tilde{H}^0, \tilde{H}^1, \tilde{H}^2$ on this new basis are obtained by the following rotation;

$$
\begin{pmatrix} \tilde{H}^0 \\ \tilde{H}^1 \\ \tilde{H}^2 \end{pmatrix} = \begin{pmatrix} \cos\beta & \sin\beta & 0 \\ -\sin\beta & \cos\beta & 0 \\ 0 & 0 & 1 \end{pmatrix} \begin{pmatrix} \phi_1 \\ \phi_2 \\ \phi_3 \end{pmatrix} \ . \tag{5}
$$

By denoting the orthogonal matrix $\mathbf{O}$ that relates this basis with the mass eigenstates H_1, H_2 and H_3 as

$$
\begin{pmatrix} \tilde{H}^0 \\ \tilde{H}^1 \\ \tilde{H}^2 \end{pmatrix} = \mathbf{O} \begin{pmatrix} H_1 \\ H_2 \\ H_3 \end{pmatrix} \ , \tag{6}
$$

maximal CP violation is defined when

$$
\mathbf{O}_{11}^2 = \mathbf{O}_{12}^2 = \mathbf{O}_{13}^2 = \frac{1}{3} \ , \tag{7}
$$

which was presented by Méndez and Pomarol[10]. Here, the matrix $\mathbf{O}$ is related with the orthogonal matrix $\mathbf{U}$, which is defined in ref.[12] to diagonalize the mass matrix of eq.(4), as follows:

$$
\mathbf{O} = \begin{pmatrix} \cos\beta & \sin\beta & 0 \\ -\sin\beta & \cos\beta & 0 \\ 0 & 0 & 1 \end{pmatrix} \mathbf{U} \ . \tag{8}
$$

In ref.[12], the constraints of the Higgs potential parameters to get maximal CP violation have been studied. In this paper, two solutions yielding maximal CP violation, which satisfy the condition of eq.(7), for $\tan\beta$[12] have been obtained;

$$\text{Sol.I}: \ \tan\beta = \frac{1}{\sqrt{2}}(\sqrt{3}-1) = 0.51\cdots \ , \quad \text{Sol.II}: \ \tan\beta = \frac{1}{\sqrt{2}}(\sqrt{3}+1) = 1.93\cdots \ , \tag{9}$$

with constraints

$$g_1 + g_2 + 2g - 2\overline{\xi} = 0 \ , \qquad g_1 = g_2 \ , \qquad \phi = \frac{\pi}{4} \ , \tag{10}$$

where $\overline{\xi} \equiv \xi/|v_1 v_2|^2$ and CP violating phase ϕ takes its maximal value as is expected. The condition of $g_1 + g_2 + 2g - 2\overline{\xi} = 0$ gives an important constraint for the neutral Higgs scalars and the charged Higgs one, since $\overline{\xi}$ determines the charged Higgs mass as follows:

$$m_{H^\pm}^2 = \overline{\xi} v^2 \ , \tag{11}$$

where $v^2 \equiv v_1^2 + v_2^2$. In addition to these constraints, there are the positivity conditions such as[15]

$$\begin{aligned} g_1 &\geq 0, \quad g_2 \geq 0, \quad g > -\sqrt{g_1 g_2}, \quad g + g' - |h| \geq -\sqrt{g_1 g_2}, \\ \xi &\geq 0, \quad g' - |h| + \overline{\xi} \geq 0, \quad \overline{\xi} - g \geq -\sqrt{g_1 g_2}. \end{aligned} \tag{12}$$

The masses of the three neutral Higgs scalars are given as

$$\begin{aligned} m_{H1}^2 &= 2g_1 \cos^4\beta + 2g_2 \sin^4\beta + 4(\overline{\xi} - g)\sin^2\beta\cos^2\beta = 2g_1 \ , \\ m_{H2}^2 &= g' + \overline{\xi} + h \ , \qquad m_{H3}^2 = g' + \overline{\xi} - h \ , \end{aligned} \tag{13}$$

in units of v^2, where the conditions in eq.(10) are used in the second equality for m_{H1}^2. We notice that the four Higgs masses are given by four parameters g_1, g', h and $\overline{\xi}$. Since the parameter h is predicted to be very small in analyses using the renormalization group equation[16], the values of m_{H2} and m_{H3} are expected to be close to each other.

In our numerical analyses, we take $m_{H2} < m_{H3}$ by fixing $h < 0$ as our convention. On the other hand, m_{H1} is not constrained.

Now, we can estimate the CP violating parameters $\mathrm{Im}Z_1$ and $\mathrm{Im}Z_2$ in THDM. These are the imaginary parts of the scalar meson fields normalization constants, Z_i, which are the column vectors in the neutral Higgs scalar vector space, defined in terms of the tree level approximation to the two-point function as follows[13]:

$$\frac{1}{v_i^2}\langle\phi_i^0\phi_i^0\rangle_q = \sum_{n=1}^{3}\frac{\sqrt{2}G_F}{q^2 - m_{Hn}^2}Z_i^{(n)} \quad (i = 1, 2) \ , \tag{14}$$

where $v_i \equiv \langle\phi_i^0\rangle_{vac}$. The CP violation factors $\mathrm{Im}Z_i^{(n)}$ are deduced to

$$\mathrm{Im}Z_1^{(k)} = -\frac{\tan\beta}{\cos\beta}u_1^{(k)}u_3^{(k)} \ , \qquad \mathrm{Im}Z_2^{(k)} = \frac{1}{\tan\beta\sin\beta}u_2^{(k)}u_3^{(k)} \ , \tag{15}$$

where $u_i^{(k)}$ denotes the $i-$th component of the $k-$th normalized eigenvector of the Higgs mass matrix. The values of $u_i^{(k)}$ are given by solving Higgs mass matrix $\mathbf{M^2}$ of eq.(4) in the case of the maximal CP violation. In the maximal CP violation, we get[12]

$$\begin{aligned} u^{(1)} &= (\cos\beta, \ -\sin\beta, \ 0) \ , \\ u^{(2)} &= (\frac{1}{\sqrt{2}}\sin\beta, \ \frac{1}{\sqrt{2}}\cos\beta, \ -\frac{1}{\sqrt{2}}) \ , \\ u^{(3)} &= (\frac{1}{\sqrt{2}}\sin\beta, \ \frac{1}{\sqrt{2}}\cos\beta, \ \frac{1}{\sqrt{2}}) \ . \end{aligned} \tag{16}$$

Using these eigenvectors, we can calculate CP violating parameters $\mathrm{Im}Z_i^{(k)}$. For the first Higgs scalar, these are zero because the third component of the eigenvector is zero as seen in eq.(16), i.e., there is no scalar-pseudoscalar interference term. We have non-vanishing values for second and third Higgs scalars (k=2,3) as follows:

$$\mathrm{Im}Z_1^{(2)} = -\mathrm{Im}Z_1^{(3)} = \frac{1}{4}(\sqrt{3}\mp 1)^2 \ , \qquad \mathrm{Im}Z_2^{(2)} = -\mathrm{Im}Z_2^{(3)} = -\frac{1}{4}(\sqrt{3}\pm 1)^2 \ , \tag{17}$$

the upper and lower signs correspond to the Sol.I and Sol.II of $\tan\beta$ in eq.(9), respectively. We notice that these values are somewhat smaller than the Weinberg's bound[13]

taking the same value of $\tan\beta$,

$$\left|\frac{\mathrm{Im}Z_1^{(2,3)}}{\mathrm{Im}Z_1^{(WB)}}\right| \simeq \begin{cases} 0.89 \\ 0.46 \end{cases} , \qquad \left|\frac{\mathrm{Im}Z_2^{(2,3)}}{\mathrm{Im}Z_2^{(WB)}}\right| \simeq \begin{cases} 0.46 \\ 0.89 \end{cases} , \tag{18}$$

where (WB) denotes the Weinberg's bounds, and the upper values and lower ones correspond to the Sol.I and Sol.II of $\tan\beta$, respectively. Thus, the Weinberg's bound does not correspond to maximal CP violation, because both $\mathrm{Im}Z_1^{(k)}$ and $\mathrm{Im}Z_2^{(k)}$ cannot approach to those bounds at the same time.

Let us discuss the EDM of the neutron in the case of maximal CP violation. The low energy CP violating interaction is described by an effective Lagrangian L_{CP}, which is generally decomposed into the local composite operators O_i of the quark and gluon fields,

$$L_{CP} = \sum_i C_i(M,\mu) O_i(\mu) \ . \tag{19}$$

Some authors pointed out[2,3] that the three gluon operator with the dimension six and the quark-gluon operator with the dimension five dominate EDM of the neutron in THDM. So, we study the effect of these two operators on the neutron EDM. Various techniques have been developed to estimate the strong-interaction hadronic effects[17,18,19,20]. The simplest one is the NDA approach[17], but it provides at best the order-of-magnitude estimates. The systematic technique has been given by Chemtob[18] for the case of the operator with the higher-dimension involving the gluon fields. We employ his technique to get the hadronic matrix elements of our operators.

Let us define the following operators:

$$O_{qg}(x) = -\frac{g_s}{2}\overline{q}\sigma_{\mu\nu}\tilde{G}^{\mu\nu}q \ , \qquad O_{3g}(x) = -\frac{g_s^3}{3} f^{abc}\tilde{G}^{a,\mu\nu}G_{\mu}^{b,\alpha}G_{\nu\alpha}^{c} \ , \tag{20}$$

where q denotes u, d or s quark. The QCD corrected coefficients are given by the

two-loop calculations[2,3] as follows:

$$
\begin{aligned}
C_{ug} &= -\frac{\sqrt{2}G_F m_u(\mu)}{128\pi^4} g_s^2(\mu)[f(z_t)+g(z_t)]\mathrm{ImZ}_2 \left(\frac{\mathrm{g_s}(\mu)}{\mathrm{g_s(M)}}\right)^{-\frac{74}{23}} , \\
C_{dg} &= -\frac{\sqrt{2}G_F m_d(\mu)}{128\pi^4} g_s^2(\mu)[f(z_t)\tan^2\beta\mathrm{ImZ}_2 - g(z_t)\cot^2\beta\mathrm{ImZ}_1] \left(\frac{\mathrm{g_s}(\mu)}{\mathrm{g_s(M)}}\right)^{-\frac{74}{23}} , \\
C_{3g} &= \frac{\sqrt{2}G_F}{256\pi^4} h(z_t)\mathrm{ImZ}_2 \left(\frac{\mathrm{g_s}(\mu)}{\mathrm{g_s(M)}}\right)^{-\frac{108}{23}} ,
\end{aligned} \tag{21}
$$

where $z_t = (m_t/m_H)^2$ and we omitt the upper-indices (k) defined in eq.(15). The functions $f(z_t)$, $g(z_t)$ and $h(z_t)$ are the two-loop integral functions, which are defined in refs.[4,5,21]. The coefficient C_{sg} is obtained from C_{dg} by repalcing m_d with m_s.

The hadronic matrix elements of the two operators are approximated by the intermediate states with the single nucleon pole and the nucleon plus one pion. Then, the nucleon matrix elements are defined as[18]

$$
\begin{aligned}
\langle N(P)|O_i(0)|N(P)\rangle &= A_i\overline{U}(P)i\gamma_5 U(P) , \\
\langle N(P')|O_i|N(P)\pi(k)\rangle &= B_i\overline{U}(P')\tau^a U(P) ,
\end{aligned} \tag{22}
$$

where $U(P)$ is the normalized nucleon Dirac spinors with the four momuntum P. By using A_i and $B_i (i = ug, dg, sg, 3g)$, the neutron EDM, d_n^γ, is written as

$$
d_n^\gamma = \frac{e\mu_n}{2m_n^2}\sum_i C_i A_i + F(g_{\pi NN}, m_n, m_\pi)\sum_i C_i B_i , \tag{23}
$$

where μ_n is the neutron anomalous magnetic moment. The function $F(g_{\pi NN}, m_n, m_\pi)$ was derived by calculating the pion and nucleon loop corrections using the chiral Lagrangian for the coupled $N\pi\gamma$ and is given in Appendix A of ref.[18]. Here, the dimensional regularization with the standard $\overline{MS}$ scheme is used for defining the finite parts of the divergent integrals. The coefficients A_i and B_i were given by the use of the large N_c current algebra and the η_0 meson dominance[18]. Then, we have

$$
A_i = f_i g_{\eta_0 NN} , \qquad B_i = -\frac{4(m_u+m_d)a_1 f_i}{F_\pi F_0} , \tag{24}
$$

with $a_1 = -(m_{\Sigma^0} - m_\Sigma)/(2m_s - m_u - m_d) \simeq -0.28$ and $F_\pi = \sqrt{2/3}F_0 = 0.186\text{GeV}$, where f_i is defined by

$$\langle \eta_0(q)|O_i(0)|0\rangle \equiv f_i q^2 \ . \tag{25}$$

The values of f_i were derived by using QCD sum rules as follows[18]:

$$f_{qg} = -0.346\text{GeV}^2 \ , \qquad\qquad f_{3g} = -0.842\text{GeV}^3 \ , \tag{26}$$

where f_{qg} denotes the flavor singlet coupling.

Now, we can calculate the neutron EDM. Our input parameters are[20]

$$\begin{aligned}
&\Lambda_{QCD} = 0.26\text{GeV} \ , \qquad (m_u, m_d, m_s) = (5.6, 9.9, 200)\text{MeV} \ , \qquad \mu = m_n \ , \\
&M = m_t = 150\text{GeV} \ , \qquad g_{\pi NN} = 13.5 \ , \qquad g_{\eta_0 NN} = 0.892 \ .
\end{aligned} \tag{27}$$

We show in fig.1 our predictions of the neutron EDM versus the ratio of the masses of the two Higgs scalars in the case of $m_{H2} = 200, \ 400, \ 600\text{GeV}$ by using Sol.I of the maximal CP violation. The predicted neutron EDM in Sol.II is almost same as the one in Sol.I. As seen in fig.1, the mass difference $\Delta m_H = m_{H3} - m_{H2}$ should be small in order to get the lower values of EDM than the experimental upper bound, $11 \times 10^{-26} e\cdot\text{cm}$[22]. We get $\Delta m_H \simeq 18\text{GeV}$, which corresponds to $|h| \simeq 0.13$, in the case of $m_{H2} = 200\text{GeV}$, $\Delta m_H \simeq 52\text{GeV}(|h| \simeq 0.73)$ in the case of $m_{H2} = 400\text{GeV}$, and $\Delta m_H \simeq 140\text{GeV}(|h| \simeq 3.12)$ in the case of $m_{H2} = 600\text{GeV}$. In order to show the effect of the relevant operators, we show the contributions of O_{ug}, $O_{dg} + O_{sg}$ and O_{3g} to the neutron EDM in fig.2 in the case of $m_{H2} = 200\text{GeV}$ by using Sol.I. As seen in fig.2, the effects of the O_{ug} and O_{3g} cancel out each other, and the $O_{dg} + O_{sg}$ contribution dominates the neutron EDM, which has already been pointed out in ref.[20]. Since the contributions of O_{ug} and O_{3g} depend only on $\text{Im}Z_2$ as seen in eq.(21), there are large difference between Sol.I and Sol.II in these contributions. However, these contributions

EPS File 08fig1.ps.ps not found

Figure 1: The predicted neutron EDM versus the ratio of m_{H2}/m_{H3} in the cases of $m_{H2} = 200$GeV(solid curve), 400GeV(dashed curve) and 600GeV(dashed-dotted curve) by using Sol.I. The horizontal dashed line denotes the experimental upper bound, $11 \times 10^{-26} e \cdot$ cm.

almost cancel out each other in the predicted total neutron EDM. On the other hand, the contribution of $O_{dg} + O_{sg}$ in Sol.I is exactly same as the one in Sol.II. Thus, both Sol.I and Sol.II give the almost same values for the predicted neutron EDM.

Now let us discuss the EDM of the electron. Barr and Zee[5] presented the two-loop Feynman diagrams which can lead to a large EDM of the charged lepton. Those diagrams involve a heavy particle, say the top quark or W boson in the loop that couples to an external photon line as follows:

$$\begin{aligned}
\left[\frac{d_e}{e}\right]_{t-loop} &= -\frac{\alpha}{12\pi^3}\sqrt{2}G_F m_e \left[f(z_t)\tan^2\beta \mathrm{Im}Z_2 + g(z_t)\cot^2\beta \mathrm{Im}Z_1\right] , \qquad (28) \\
\left[\frac{d_e}{e}\right]_{W-loop} &= -\frac{\alpha}{32\pi^3}\sqrt{2}G_F m_e \left[3f(z_W) + 5g(z_W)\right]\left(\sin^2\beta\tan^2\beta \mathrm{Im}Z_2 + \cos^2\beta \mathrm{Im}Z_1\right) ,
\end{aligned}$$

where $z_t = (m_t/m_H)^2$ and $z_W = (m_W/m_H)^2$. The loop-functions $f(z)$ and $g(z)$ are the same ones as those in eq.(21). Chang, Keung and Yuan[8] have given the complete set of two-loop diagrams in the multi-Higgs-doublet model. They calculate the effective CP violating $HZ\gamma$ vertex in addition to the $H\gamma\gamma$ one induced by the unphysical charged Higgs and the W contribution. In this paper, we use their results[8] instead of eq.(28), however the structures of $\tan\beta$ and $\mathrm{Im}Z_i$ in eq.(28) being unchanged.

In the case of maximal CP violation, the loop contributions of W and the unphysical

EPS File 08fig2.ps.ps not found

Figure 2: The components of the predicted neutron EDM versus the ratio of m_{H2}/m_{H3} in the cases of $m_{H2} = 200$GeV by using Sol.I. The thick-solid curve denotes the absolute values of the total contribution. The thin-solid curve, the dashed curve and the dashed-dotted curve denote the contribution from O_{ug}, $O_{dg} + O_{sg}$ and O_{3g} operators, respectively.

EPS File 08fig3.ps.ps not found

Figure 3: The predicted electron EDM versus the ratio of m_{H2}/m_{H3} in the cases of $m_{H2} = 200$GeV(solid curve), 400GeV(dashed curve) and 600GeV(dashed-dotted curve). The experimental upper bound $(-0.3 \pm 0.8) \times 10^{-26} e \cdot \mathrm{cm}$ is outside the figure.

charged Higgs boson vanish because $\sin^2\beta\tan^2\beta \mathrm{Im} Z_2 + \cos^2\beta \mathrm{Im} Z_1$ is zero in both Sol.I and Sol.II. So, the elctron EDM is given by only the top-quark loop contribution, which is exactly same in both Sol.I and Sol.II. We show in fig.3 the predicted electron EDM versus the ratio of the two Higgs scalars in the case of $m_{H2} = 200,\ 400,\ 600$GeV. Thus, the magnitude of the electron EDM does not go over the experimental bound $(-0.3 \pm 0.8) \times 10^{-26} e{\cdot}\mathrm{cm}$[22] even if the mass difference of the two Higgs scalars is considerably large. Summary is given as follows. We have studied the EDM of the neutron and the electron in the two Higgs doublet model, in the case of CP symmetry being violated maximally in the neutral Higgs sector. The maximal CP violation is realized under the fixed values of $\tan\beta$ with two constraints of parameters in the Higgs

potential. We have taken account of the Weinberg's operator $O_{3g} = GG\tilde{G}$ and the operator $O_{qg} = \overline{q}\sigma\tilde{G}q$ for the neutron, and Barr-Zee diagrams for the electron. It is found that the predicted neutron EDM could be considerably reduced due to the destructive contribution of the two Higgs scalars leading to the lower value than the experimental upper bound, while the predicted electron EDM is smaller in one order than the experimental bound. Since our predicted value of the neutron EDM lies around the present experimental bound, we expect its experimental improvement to reveal the new physics beyond SM.

Acknowledgments

One of us(M.T) thanks the particle group at Institut für Theoretische Physik in Universität Wien, especially, Prof.H. Pietschmann, for kind hospitality. This research is supported by the Grant-in-Aid for Scientific Research, Ministry of Education, Science and Culture, Japan(No.06220101 and No.06640386).

References

[1] M.Kobayashi and T.Maskawa, Prog. Theor. Phys. **49**(1973) 652.

[2] S. Weinberg, Phys. Rev. Lett. **63**(1989)2333.

[3] J.F. Gunion and D. Wyler, Phys. Letts. **248B**(1990)170.

[4] A. De Rújula, M.B. Gavela, O. Pène and F.J. Vegas, Phys. Lett. **245B**(1990)640;
N-P. Chang and D-X. Li, Phys. Rev. **D42**(1990)871;
D.Chang, T.W.Kephart, W-Y.Keung and T.C.Yuan, Phys.Rev.Lett. **68**(1992)439;
M. J. Booth and G. Jungman, Phys. Rev. **D47**(1993)R4828.

[5] S.M. Barr and A. Zee, Phys. Rev. Lett. **65**(1990)21;
S.M. Barr, Phys. Rev. Lett. **68**(1992)1822; Phys. Rev. **D47**(1993)2025.

[6] For a text of Higgs physics see J.F. Gunion, H.E. Haber, G.L.Kane and S. Dawson, *"Higgs Hunter's Guide"*, Addison-Wesley, Reading, MA(1989).

[7] G.C. Branco and M.N. Rebelo, Phys. Lett. **160B**(1985)117.

[8] J.F. Gunion and R. Vega, Phys. Lett. **251B**(1990)157;
D. Chang, W-Y. Keung and T.C. Yuan, Phys. Rev. **D43**(1991)14;
R.G. Leigh et al., Nucl. Phys. **B352**(1991)45.

[9] B. Grządkowski and J.F. Gunion, Phys. Lett. **287B**(1992)237;
B. Grządkowski and J.F. Gunion, Phys. Lett. **294B**(1992)361;
B. Grządkowski and W-Y. Keung, Phys. Lett. **319B**(1993)526;
C. Schmidt and M. Peskin, Phys. Rev. Lett. **69**(1992)410;
R. Cruz, B. Grządkowski and J.F. Gunion, Phys. Lett. **289B**(1992)440;
D. Atwood, G. Eilam and A. Soni, Phys. Rev. Lett. **70**(1993)1364;

B. Grządkowski , preprint at Warsaw University, IFT07/94(1994),hep-ph@9404330.

[10] A. Méndez and A. Pomarol, Phys. Lett. **272B**(1991)313.

[11] C.D. Froggatt, R.G. Moorhouse and I.G. Knowles, Phys. Rev. **D45**(1992)2471;

Nucl. Phys. **B386**(1992)63;

A. Pomarol and R. Vega, Nucl.Phys. **B413**(1994)3.

[12] G.C. Joshi, M. Matsuda and M. Tanimoto, UWThPh-1994-25, AUE-04-94,

hep-ph@9407255(1994), to be published in Phy. Lett. **B**.

[13] S. Weinberg, Phys. Rev. **D42**(1990)860.

[14] H. Georgi, Hadr. J. Phys. **1**(1978)155.

[15] B. Kastening, Private communications and see the preprint(hep-ph@9307224).

[16] M.A. Luty, Phys. Rev. **D41**(1990)2893;

C.D. Froggatt, I.G. Knowles, R.G. Moorhouse, Phys. Lett. **249B**(1990)273;

M. Chemtob, Z. Phys. **C60**(1993)443.

[17] A. Manohar and H. Georgi, Nucl. Phys. **B234**(1984)189.

[18] M. Chemtob, Phys. Rev. **D45**(1992)1649.

[19]X-G. He, B.H.J. Mckellar and S. Pakvasa, Mod. Phys. **A4**(1989)5011;

I.I. Bigi and N.G. Uraltsev, Nucl. Phys. **B353**(1991)321.

[20] T.Hayashi, Y.Koide, M.Matsuda and M.Tanimoto, Prog.Theor.Phys.**91**(1994)915.

[21] D.A. Dicus, Phys. Rev. **D41**(1990)999;

D. Chang, W-Y. Keung and T.C. Yuan, Phys. Lett. **251B**(1990)608.

[22] Particle Data Group, Phys. Rev. **D50**(1994)1218.